TITLE: Maintaining Finger Dexterity in the Cold: A Comparson of Passive, Direct and Indirect Hand Heating Methods

Maintaining Finger Dexterity in the Cold: A Comparison of Passive, Direct and Indirect Hand Heating Methods

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Summary

Examined finger dexterity performance and extremity comfort during cold exposure while an attempt was made to prevent or minimize hand cooling by either passive hand insulation (thin, knitted gloves and Arctic mitts), direct hand heating (electrically heated gloves), or indirect hand heating (heating the torso in an attempt to increase blood flow to the hands) with and without gloves. Eight male subjects were exposed to -25°C air (wind ~ 2 km/h) for three hours. A three-layer, Arctic clothing ensemble was worn during all experiments. Finger temperature, finger blood flow, toe temperature, rectal temperature, and finger dexterity were measured. Indirect hand heating was found to be superior to passive and direct hand heating because not only was finger comfort and finger dexterity maintained, but the whole body (toes included) remained comfortable for the full three-hour session. In addition, with indirect hand heating, fine finger dexterity tasks can be performed barehanded, if necessary, without the risk of cold injury.

Introduction

There is a military need for a hand heating system that will keep the hands warm and still allow for good finger dexterity. Soldiers will often remove their mitts to improve finger dexterity and will work with thin contact gloves to do a task more effectively. However, removing the bulky mitts or gloves can lead to finger discomfort or pain due to the decreased insulation over the hands. Frostbite is also a possibility, depending on the ambient condition and the length of the cold exposure. Therefore, removing bulky gloves or mitts to perform a task with thin contact gloves is not an ideal solution.

There are also some situations in which soldiers may remove their bulky gloves or mitts and their thin contact gloves in order to perform fine finger dexterity work with their bare hands. For example, a medic out in the battlefield may work barehanded to treat a soldier's wound. However, by working barehanded the medic is at a greater risk of cold injury. Therefore, it would be nice to have a hand heating system that could keep the hands warm even when there is minimal or no insulation over the hands!

It is especially difficult to keep the hands of soldiers warm and comfortable when they are inactive and are not generating very much metabolic heat. The extremities are the first to cool during periods of inactivity. A sniper, for example, may have to spend a prolonged period of time outdoors in the cold with little or no body movement while focusing on a target. It is important that the soldier remain focused on the target and not be distracted by the finger pain or discomfort that might occur while outside on a cold day. In addition, the sniper's shooting accuracy may be decreased if his core temperature decreases enough to cause shivering to occur. The involuntary muscle contractions that occur during shivering are definitely undesirable when the sniper is trying to hold his rifle steady. Therefore, it would be ideal to keep the body and fingers comfortable in order to maximize shooting performance.

Purpose

To examine finger dexterity performance and extremity comfort during cold exposure while an attempt was made to prevent or minimize hand cooling by either passive hand insulation (thin, knitted gloves and Arctic mitts), direct hand heating (electrically heated gloves), or indirect hand heating (heating the torso in an attempt to increase blood flow to the hands).

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Methods

Subjects

Eight healthy, non-smoking male volunteers with the following characteristics were recruited (mean±S.D.): age 32.8±7.4 years, height 176.4±6.3 cm, weight 82.4±7.5 kg, and body surface area 1.99±0.11 m^2. Body surface area was calculated using the formula of Dubois and Dubois (5). All subjects were medically screened by a physician at DCIEM before being asked for their written consent. This study was approved by the Human Ethics Committee at the Defence and Civil Institute of Environmental Medicine (DCIEM).

Ambient Condition and Clothing Worn

Subjects sat in a chair while exposed to an ambient temperature of -25°C (wind ~ 2 km/h) for three hours during all tests except when finger skin temperature (T_{fing}) reached 6°C, at which point the exposure was terminated. A three-layer, Arctic clothing ensemble [0.556 $m \cdot k^2/W$ (3.6 Clo)] was worn during all experiments. The three-layer system included a fleece garment (first layer), an uninsulated inner parka and pants (second layer), and an insulated outer parka and pants (third layer). A thin pair of long, cotton underwear was worn under the fleece pants. Standard CF mukluks, woolen socks, and a balaclava were also worn. The 3.6 Clo Arctic clothing insulation values did not take into account the long, cotton underwear worn under the fleece pants that have a Clo value of 0.3 (0.05 $m^2 \cdot °K \cdot W^{-1}$).

Hand Heating Conditions

Subjects were exposed to 4 conditions designated as passive, direct, indirect-passive, and indirect-bare. Each cold exposure was initiated at approximately 10 a.m. each morning. During the passive condition, thin, knitted gloves and Arctic mitts covered the hands. During the direct condition, the hands were actively heated with thin, electrically heated gloves and Arctic mitts were worn over the gloves. Finally, during the two indirect conditions, an electrically heated vest was used to actively heat the body in an attempt to increase the vasodilative response in the hands. During indirect-passive, the hands were insulated with thin, knitted, non-heated gloves and Arctic mitts, whereas during indirect-bare, the hands were bare during the entire 3 hour cold exposure. The tests were done one week apart over a time period spanning from January to July. The extremity temperature responses observed during this study are representative of a mixed, male population in which some subjects may have had a greater degree of peripheral cold acclimatization as a result of spending more time working or playing outdoors during the winter.

Design of Electrically Heated Vest and Gloves

The electrically heated vest consisted of 10 Kapton® insulated flexible heaters (Omega Engineering, Stamford, CT, USA) fixed around the torso as follows: two heaters (each 12 x 20 cm) on the chest, two heaters on the abdomen (each 8 x 30 cm), one heater at each side of the torso (each 8 x 20 cm), two heaters over the shoulder area (each 8 x 30 cm), and two heaters on the back (each 15 x 30 cm). The heaters covered a total area of 0.266 m^2. The heaters were not in direct contact with the skin, but inside a fire resistant pocket made of Nomex® fabric. In addition, a one centimeter layer of Thinsulate® insulation was placed inside the pocket on the outer surface of the heater. The Thinsulate® insulation was covered by a piece of reflective mylar to help reflect the radiative heat back to the torso. Once the heaters were placed inside the pockets, the pockets were sewn together to form a vest that covered a total area of 0.366 m^2. A tight, short-sleeved lycra body suit, which extended down to the mid-thigh level, was worn over the heaters to optimize the contact between the skin and the heaters. The electrically heated gloves used were constructed using a 300 strand tinsel wire that was knitted into a tight-fitting, nylon glove (Rapier Missile Glove, Vacuum Reflex Ltd., Suffolk, UK). The heating wire of each glove surrounded each finger and partially covered the back of the hand. The palms were not heated.

In regard to the electrically heated vest, pre-selected voltages were sent by five current-limiting power supplies (two model 6030A, 0-200V/0-17A, 1000W; three model 6034A, 0-60V/0-10A, 200W; Hewlett Packard) to the five pairs of heaters to achieve a skin temperature of 42±0.5°C under each heater. The power supplies were controlled by a computer that allowed the user to input the desired voltage for each pair of heaters. To ensure that the skin temperature under the heaters did not reach 45°C at any time, the computer turned off the heater completely if skin temperature reached 44°C. The electrically heated glove heater power was adjusted manually so that the mean finger skin temperature (T_{fing}) was the same as the T_{fing} established during the indirect-passive hand heating condition.

Finger Dexterity Tests

During the three-hour cold exposure, the subjects were asked to perform either a C-7 rifle disassembly and assembly task (C-7 rifle task) or a Purdue Pegboard test (PP test) every 30 min. The C-7 rifle task was done at time 0, 60, 120, and 180 min, whereas the PP test was done at time 30, 90, and 150 min. The C-7 rifle task was chosen because it was representative of the type of finger dexterity task that might be carried out by soldiers in the field. Subjects were required to do a "detailed stripping" of the rifle as outlined in "The Warrior" Canadian Forces combat survival manual (1). This involves an eight-step "field strip" (step nine was omitted for this experiment) and a six-step "detailed strip" (step three was omitted for this experiment). A total of 10 pieces (primarily made from metal) were disassembled. The process was then repeated in the reverse order to reassemble the C-7 rifle.

The PP test, on the other hand, is an extensively used fine finger dexterity test, which has been shown to be a reliable and valid measure of finger dexterity over the years (2, 9). The Purdue Pegboard consists of a pegboard with two columns of small holes down the middle of the board and four small cups along the top of the board that contain small metal pins, washers, and collars. The object of the PP test is to put together as many assembled units as possible in a one min period (one assembled unit consists of: pin, washer, collar, washer). The subjects were asked to perform three trials of the one-min test with approximately a 15-30 second break between each trial. A PP score was recorded for each trial. In calculating the PP score, the subject was awarded one point for each piece (i.e., pin, washer, or collar) placed on the PP board. In Fig. 5, each data point represents the average of three trials. During condition indirect-bare, the tests were done barehanded, whereas during the other three conditions, the Arctic mitts were removed, but the knitted, contact gloves were kept on for the duration of the dexterity tests. During the completion of the three PP test trials, the hands were exposed to the -25°C air for approximately four min, whereas the C-7 rifle task took approximately one-to-three min to complete.

The subjects were taught how to do the C-7 test and the PP test by the investigators during a 45 min training session which was arranged with the subject prior to start of the experimental sessions. In addition to the training session, during the experimental sessions, the subjects were asked to practice the C-7 and PP tests prior to each entry into the cold chamber. The subjects practiced the tests until a plateau in performance was observed. The subjects practiced the tests outside the cold chamber while wearing the same upper body CF Arctic clothing worn inside the cold chamber, but they were exposed to a 25°C ambient environment. Only shorts covered the lower body during the practice session.

Physiological Variables Measured

During the three-hour cold exposure, the following physiological variables were measured:

Finger skin temperature (T_{fing}) was measured using a cylinder-shaped thermistor (1.9 mm x 8.6 mm; Baxter 400 Series rectal/esophageal probe without the protective sheath covering (time constant = 0.9 seconds in well-stirred water), Baxter Healthcare Corp., Deerfield, IL, USA). A probe was placed on the pad of the "ring" fingertip of each hand. It was held in position on the skin with double-sided adhesive tape (3M Double-Stick Discs, 3M Medical Division, St. Paul, MN, USA) and a thin strip of surgical tape (3M Transpore Tape, 3M Canada Inc., London, ON, Canada) without constricting the finger.

Toe skin temperature (T_{toe}) was measured using a DCIEM lab-made, banjo probe (diameter = 10.2 mm, max height = 4.7 mm) that contains a protruding YSI 44004 thermistor bead. The probe is similar in shape to the YSI 081 standard surface probe (Yellow Springs Instruments, Yellow Springs, OH, USA), but it has a plexi-glass contact surface (instead of the stainless steel surface used in the YSI probe) and it has a time constant of 5 seconds in well-stirred water. A probe was placed on the medial side of the big toe of each foot. The toe thermistor was held in place against the skin with surgical tape (3M Transpore Tape, 3M Canada Inc., London, ON, Canada).

Rectal temperature (T_{re}) was measured via a thermistor (Pharmaseal 400 series, Baxter, Valencia, CA, USA) inserted 15 cm beyond the anal sphincter.

Measurements of T_{fing}, T_{toe}, and T_{re} were made five times per min over the course of three hours using a data acquisition system (model 3497A data acquisition/control unit; Hewlett Packard). An average value was printed out each min.

Finger blood flow (Q_{fing}) was measured using a 780 nm laser Doppler flowmeter probe (PF4001 Laser Doppler Flowmeter, Perimed, Stokholm, Sweden). A blood flow probe was placed next to each finger temperature thermistor. The unit of measurement used to represent the skin blood flow is the perfusion unit (PU). This is a relative unit of blood flow. A calibration standard is used to adjust the laser Doppler flowmeter readings to coincide with the readings obtained with a motility standard. Q_{fing} was measured 15 times per minute for three hours and an average Q_{fing} was taken every minute.

Statistical Analyses

A two-way ANOVA for repeated measures was used to compare conditions indirect-passive, direct and passive. The independent variables were "heating method" and "time". A two-way ANOVA was also used to compare the indirect-passive and indirect-bare conditions. The independent variables were "hand insulation" and "time". These analyses were done for the dependent variables C-7 rifle time, PP score, T_{fing}, T_{toe}, and T_{re} from 0 to 180 min. Five-min averages were calculated for the 180 min of data so that time 2, 7, 12 min, etc. represented the data from 0 to 4 min, 5 to 9 min, 10 to 14 min, etc. Five-min averages were not calculated for the finger dexterity data (i.e., C-7 rifle time and PP score) because data for these variables were collected every 30 to 60 min. Results were considered statistically significant at $p \leq 0.05$ (using the Greenhouse-Geisser adjustment for repeated measures). A Newman Keuls post-hoc test was used to determine if there was a significant difference in any of the dependent variables from 0 to 180 min. All values are presented as mean±SE.

Results

Finger skin temperature (Fig. 1)

T_{fing} was maintained at an average of 35±0.1°C for three hours during the indirect-passive and direct hand heating conditions, whereas during the indirect-bare hand heating condition, T_{fing} cycled between 24±1.3°C and 33±0.9°C for three hours. The hands were very comfortable. During the passive heating condition, T_{fing} decreased from 35±0.3°C to 12±0.5°C from the beginning to the end of the exposure and remained below 15°C for the last 90 min of the cold exposure. This was very uncomfortable for most subjects.

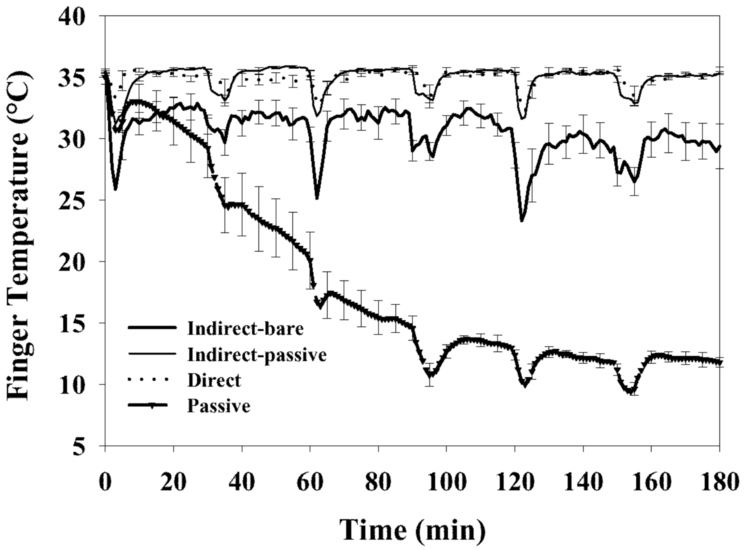

Fig. 1 *Mean finger skin temperature as a function of type of heating over time during exposure to -25°C air. Mean±SE (n=8).*

Finger blood flow (Fig. 2)

Q_{fing} was maintained at 223±28 PU and 255±19 PU during the indirect-bare and indirect-passive hand heating conditions, respectively, whereas during direct hand heating, Q_{fing} decreased from 213±21 PU to 27±5 PU from time 10 to 180 min. During passive heating, Q_{fing} decreased from 191±50 PU to 25±5 PU from time 10 to 180 min. Notice that during the direct hand heating method, blood flow was very low relative to the indirect heating-passive insulation condition, even though finger temperature was maintained, on average, at 35±0.1°C in both conditions. Hence, this shows that electrically heated gloves only heat the surface of the hand. During the dexterity tests, the Q_{fing} data was not presented due to movement artefacts.

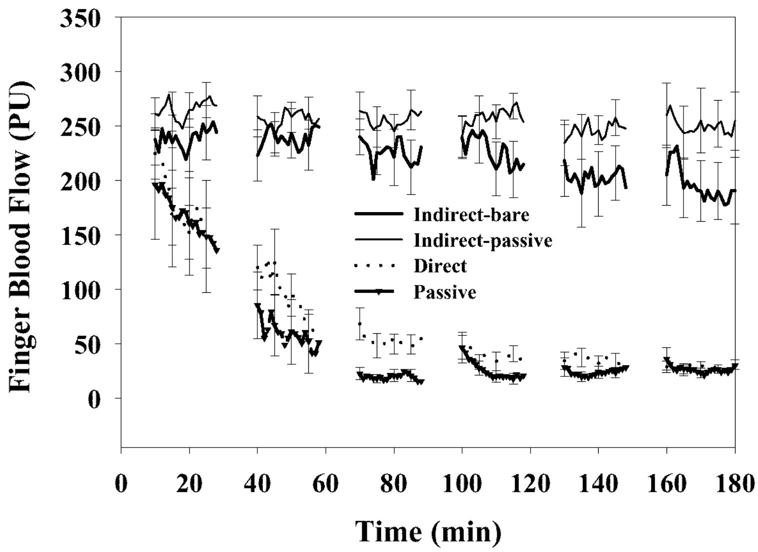

Fig. 2 *Mean finger blood flow as a function of type of heating over time during exposure to -25°C air. Mean±SE (n=8).*

Toe skin temperature (Fig. 3)

T_{toe} was maintained at 33±0.2°C during the indirect-passive heating condition, whereas during the indirect-bare condition, T_{toe} decreased from 33±1.0°C to 28±1.9°C over the course of three hours. During the passive and direct conditions, T_{toe} decreased from 33±1.0°C to 9±0.3°C from the start to the end of the exposure. T_{toe} was ≤ 15°C during the last 90 min of the cold exposure.

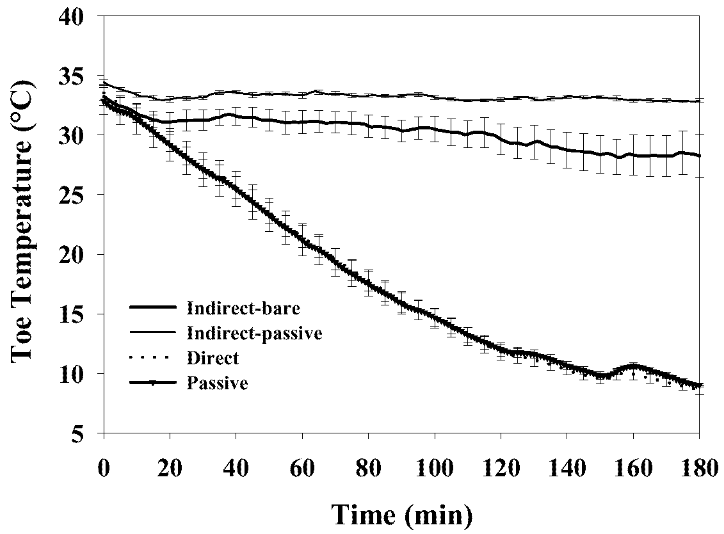

Fig. 3 *Mean toe temperature as a function of type of heating over time during exposure to -25°C air. Mean±SE (n=8). Direct condition plot is directly below passive condition plot.*

Δ Rectal temperature (Fig. 4)

During the indirect-passive heating condition, T_{re} increased by 0.23±0.04°C after an hour, relative to the start of the experiment, and then slowly decreased back down to its original value (at time 0 min) by time 180 min. There was no significant change in T_{re} during the indirect-bare condition. During the direct and passive conditions, T_{re} decreased significantly by 0.64±0.06°C and 0.57±0.08°C, respectively, by time 180 min.

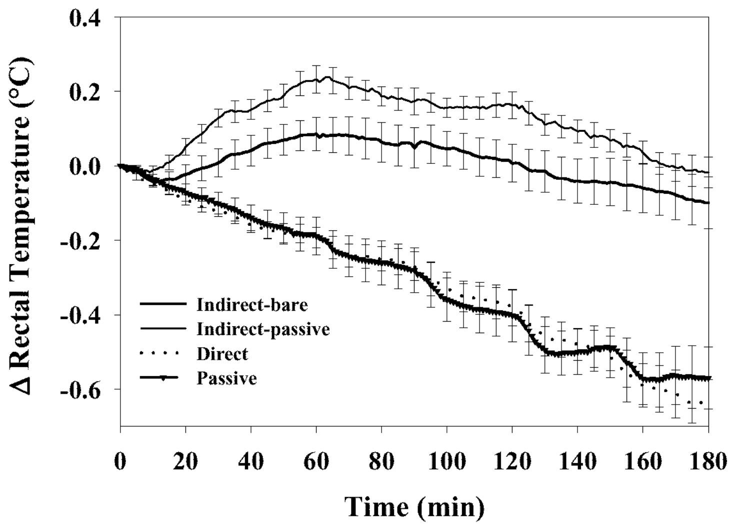

Fig. 4 *Mean change in rectal temperature as a function of type of heating over time during exposure to -25°C air. Mean±SE (n=8).*

Finger dexterity performance

Purdue Pegboard Score (Fig. 5) and C-7 Rifle Test Time (Fig. 6)

During the Purdue Pegboard finger dexterity tests, the passive hand heating condition was the only condition in which there was a significant decrement in finger dexterity over time (40% decrease after 150 min, relative to performance at time 30 min). At time 150 min, the Purdue Pegboard (PP) score was not significantly different between conditions indirect-passive and direct. During the indirect-passive and direct hand heating conditions, PP score remained stable from time 30 to 150 min at 20±2 and 18±2 points, respectively, whereas during the passive condition, PP score decreased significantly from 18±3 points at time 30 min to 11±1 points by time 150 min. During indirect-bare, PP score remained relatively stable at 48±3 points. Finger dexterity improved by 60% when the hands were bare compared to wearing gloves (i.e., compare PP scores between indirect-passive and indirect-bare). This is in agreement with Havenith and Vrijkotte's (6) finding that finger dexterity decreases by up to 70% when gloves were worn compared to bare-hand performance.

During the C-7 rifle finger dexterity tests, the passive hand heating condition, once again, was the only condition in which there was a significant decrement in finger dexterity over time (30% decrease after 180 min, relative to performance at time 0 min). It should be noted that, unlike the Purdue Pegboard test, there is an inverse relationship between finger dexterity and the rifle test time. That is, a higher rifle time corresponds to a poorer dexterity performance because it takes the subject a longer period of time to disassemble and reassemble the rifle. At time 180 min, the C-7 rifle test time was not significantly different between conditions indirect-passive and direct. During the indirect-passive and direct hand heating conditions, C-7 rifle test time remained stable at 96±5 and 98±6 sec, respectively, whereas during the passive condition, C-7 rifle test time increased significantly from 104±6 sec at time 0 min to 144±19 sec by time 180 min. During indirect-bare, C-7 rifle time remained relatively stable at 90±5 sec. Finger dexterity was not improved when the hands were bare compared to wearing gloves (i.e., compare C-7 rifle test scores between indirect-passive and indirect-bare) most likely because the C-7 rifle test is a test of gross finger/hand dexterity as opposed to a test of fine finger dexterity (i.e., the Purdue Pegboard test).

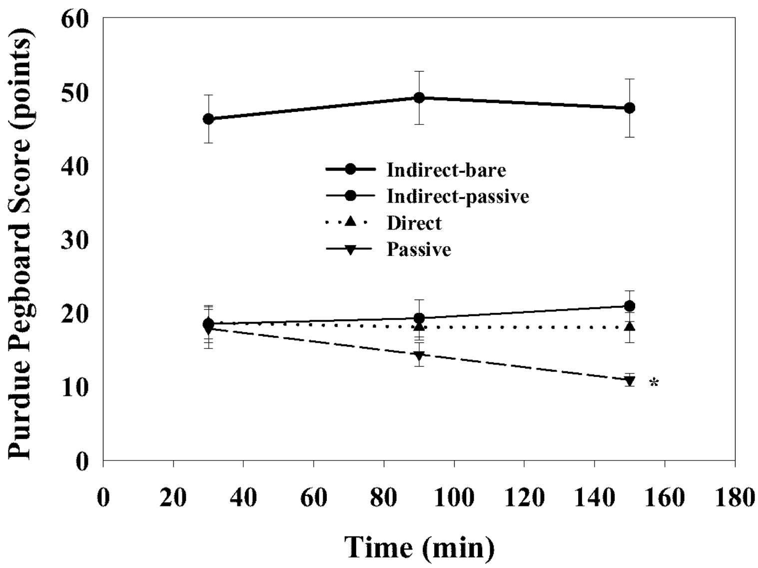

Fig. 5 *Mean Purdue Pegboard (PP) score as a function of type of heating over time during exposure to -25°C air. Mean±SE (n=8). * significant difference in PP score during passive hand heating condition at time 150 min relative to PP score during direct hand heating condition at time 150 min.*

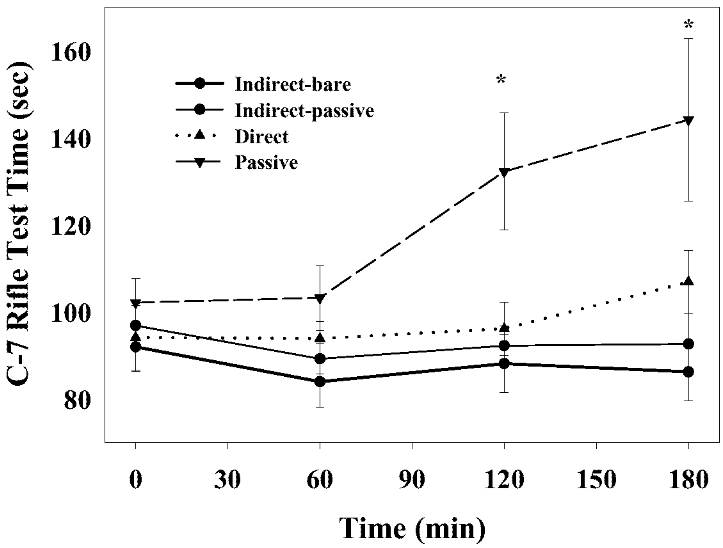

Fig. 6 *Mean C-7 Rifle Test time as a function of type of heating over time during exposure to -25°C air. Mean±SE (n=8). * significant difference in C-7 rifle test time during passive hand heating condition at time 120 and 180 min relative to C-7 rifle test time during direct hand heating condition at time 120 and 180 min.*

Discussion

Indirect hand heating (torso heating) has many advantages over passive (gloves and Arctic mitts) and direct (electrically heated gloves) hand heating. Most notably, the ability to maintain extremity comfort, finger dexterity, and body comfort (no shivering observed) in the cold (-25°C) while only wearing thin, contact gloves. In addition, with indirect hand heating, finger and toe temperatures remain comfortable (>25°C) without the use of any direct auxiliary hand/foot heating devices which are prone to wear and tear during repetitive work in the cold. Another problem with electrically heated insoles/socks is that the feet may be comfortable when an individual sits in the cold, but the feet may be too hot when pressure is applied to the sole of the foot by standing (7). Finally, indirect hand heating can maintain finger dexterity and finger comfort even when the hands are bare. This allows a soldier to perform fine finger dexterity work, while minimizing/eliminating the risk of frostbite.

In the present study, direct hand heating was effective in maintaining finger dexterity for three hours during exposure to -25°C air, even though finger blood flow was minimal. This seems to suggest that finger dexterity can be maintained as long as finger skin temperature is relatively high, regardless of finger blood flow; however, such a conclusion cannot be made without considering the effect of forearm muscle temperature on finger dexterity. LeBlanc (8) found that a cool forearm (muscle temperature not reported) can significantly decrease finger dexterity (due to the effect of muscle cooling on finger movement) even if the hand is immersed in 33°C water. Finger dexterity will most likely decrease, regardless of a high finger skin temperature, once forearm muscle temperature falls below a certain temperature threshold. A recent study found that finger dexterity was not affected (when finger skin temperature was maintained above 30°C) even if the forearm muscle temperature was decreased to 30°C (3). Therefore, the forearm temperature threshold for a decrease in finger dexterity to be observed is below 30°C.

Hence, due to the effect of forearm cooling on finger dexterity, a decrement in finger dexterity may have been observed with direct hand heating if less clothing insulation was worn. In addition, the earlier, and possibly greater intensity of shivering observed with less insulation may have directly affected finger dexterity performance due to the involuntary muscle movements that would affect hand/finger steadiness. A previous study (done at the same ambient temperature as the present study) found that whole-body shivering occurred during the last two hours of a three-hour session when 2.6 Clo was worn over the body (4). Indirect hand heating may be more effective in maintaining finger dexterity (relative to direct hand heating) when the body clothing insulation is reduced somewhat compared to the insulation worn during the present study. Further research is needed to answer some of these proposed hypotheses.

Conclusion: Indirect hand heating is superior to passive and direct hand heating if it is necessary to do fine finger dexterity work in the cold for an extended period of time.

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